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THE EARTH'S CRUST AND ISOSTASY

By William Bowie
U. S. Coast and Geodetic Survey

It would be interesting to trace the different views which have been held, throughout past ages, regarding the condition of the outer and inner portions of the earth. For the purposes of this article it suffices to say that the belief that there is some difference between the outer portion and the inner portion of the earth and, therefore, a distinct crust, has always been maintained and is even today well fixed in our minds.

The earth's crust was originally pictured as a thin veneer floating on a molten interior. This conception must be modified to agree with modern results based upon accumulated geophysical observations and measurements made during the last few decades. For example, the observations made by seismologists, respecting the time of transmission of earthquake waves, prove that the interior substance is solid and not molten. Again, the observations upon the earth's tides as caused by the sun and moon indicate very clearly that the interior of the earth is not molten. It has been computed by investigators in seismology and tides that the earth, as a whole, has at least the rigidity of steel.

Deflections of the Vertical

It has been known for a long time that whenever an astronomic station connected with a net of triangulation is located near a mountain range, a large deflection of the vertical occurs. The *deflection of the vertical* is a term applied to the deviation of the plumb line (to which all astronomic observations are referred), from the normal to the mean surface of the earth or the ellipsoid. The triangulation, being a direct measurement made with instruments of precision and by highly skilled technicians, will carry geographic positions throughout the net with a very high degree of accuracy; but, when this triangulation is connected with astronomic stations which are influenced by mountains or other elevated masses of land, it will be found that the latitudes and longitudes carried by the triangulation will differ materially from the latitudes and longitudes determined by the astronomic observations.

What is the reason for this discrepancy? It is a well-known fact that a mountain mass attracts a particle just as the earth as a whole does. The attractions of the mountain mass and the earth are in proportion to their respective masses and inversely proportional to the squares of the distances of their centers from the particle on which they are acting. At-

tempts were made many years ago to correct the astronomic observations for the effect on the plumb line of the masses above sea level. The effect of applying the correction for the attraction of the mountain masses to the astronomic determinations was to make the difference between the astronomic and the geodetic positions have the opposite sign, although making it somewhat smaller numerically.

Archdeacon Pratt, in his geodetic investigations about the middle of the last century,[1] was forced to the conclusion that the mountains did not attract the plumb line to the extent that their masses and distances from the station would seem to justify one in believing. He expressed the view that the mountains acted as if there were vast voids below them. Of course, Pratt did not believe that there are actual voids; but he did believe that there is lighter matter (commonly called a "deficiency" of matter) under the mountains which, to a certain extent, neutralizes the attractive effect of the mountains themselves.

This idea had been hinted at by other writers[2] before Pratt but not in such a definite way, and it was some years before the idea gained much favor with geologists and geophysicists.

One of the early advocates of the theory that there is a deficiency of matter under mountain areas and that there is an excess of material or density under the oceans, was Major C. E. Dutton, of the U. S. Geological Survey. In 1889, in a paper before the Philosophical Society of Washington entitled "On Some of the Greater Problems of Physical Geology,"[3] he discussed at length the condition of the outer portion of the earth and strongly advocated the theory that at some depth below sea level there is a state of equilibrium or of equal pressure in the earth's crust. He believed that unit columns of the outer portion of the earth exert the same pressure on an imaginary surface at an unknown depth regardless of whether the columns are under the oceans, the coastal plains, the plateaus, or the mountains. Dutton used the term "Isostasy," meaning equal pressure, for this condition of crustal equilibrium.

Dutton's views on the subject of isostasy had a very stimulating influence on the geologists and physiographers of his time. Among others who wrote on the same subject were Gilbert, McGee, Putnam, Ransome, and

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[1] J. H. Pratt: On the Attraction of the Himalaya Mountains, and of the Elevated Regions Beyond Them, Upon the Plumb-Line in India, *Phil. Trans. Royal Soc. of London*, Vol. 145, 1855, pp. 53–100.

Idem: On the Influence of the Ocean on the Plumb-Line in India, *ibid.*, Vol. 149, 1859, pp. 779–796.

Idem: On the Deflection of the Plumb-Line in India Caused by the Attraction of the Himalaya Mountains and of the Elevated Regions Beyond; and Its Modification by the Compensating Effect of a Deficiency of Matter Below the Mountain Mass, *ibid.*, Vol. 149, 1859, pp. 745–778.

Idem: On the Constitution of the Solid Crust of the Earth, *ibid.*, Vol. 161, 1871, pp. 335–357.

[2] [Pierre] Bouguer: La figure de la terre, déterminée par les observations de Messieurs Bouguer et de la Condamine, etc., Paris, 1749, p. 364.

M. Petit: Sur la densité moyenne de la chaîne des Pyrénées et sur la latitude de l'Observatoire de Toulouse; *Comptes Rendus de l'Acad. des Sci.* [*de Paris*], Vol. 29, 1849, pp. 729–734.

R. G. Boscovich, De Litteraria Expeditione per Pontificiam Ditionem, Rome, 1755, p. 475; quoted in Isaac Todhunter: A History of the Mathematical Theories of Attraction and the Figure of the Earth, from the Time of Newton to That of Laplace (2 vols., London, 1873), Vol. 1, p. 313.

[3] *Bull. Philos. Soc. of Washington*, Vol. 11, 1892, pp. 51–64.

Willis.[4] Putnam was the first investigator to attempt to give a quantitative measure of the extent to which the earth's outer portion is in equilibrium.

In the early part of the present century Hayford began his remarkable isostatic investigations while connected with the U. S. Coast and Geodetic Survey, in charge of geodetic operations. He used the connected triangulation of the United States and numerous astronomic latitudes, longitudes, and azimuths in a study of the effect of the theory of isostasy, or the isostatic condition of the earth's crust, on the figure of the earth. Hayford issued two reports covering the details of those investigations,[5] which outline the methods employed by him and the conclusions reached. In addition to these reports, he has written a number of articles for the scientific press, dealing with the results of his investigations.[6]

In 1909 I was stationed at the office of the Coast and Geodetic Survey, Washington, D. C., as assistant to Hayford in the Division of Geodesy, and together we made a study of the effect of the isostatic condition of the earth's crust on the intensity of gravity.[7]

Important investigations, dealing with the earth's crust and the theory of isostasy,[8] have been made in India by the officials of the Trigonometrical Survey of India. It may be said that the work in India and that in the United States supplement and confirm each other.

[4] G. K. Gilbert: The Strength of the Earth's Crust [Abstract], *Bull. Geol. Soc. of America*, Vol. 1, 1889, pp. 23–27.

Idem: Notes on the Gravity Determinations Reported by Mr. G. R. Putnam, *Bull. Philos. Soc. of Washington*, Vol. 13, 1895–99, pp. 61–75.

W J McGee: The Gulf of Mexico as a Measure of Isostasy, *Amer. Journ. of Sci.*, No. 261, Ser. 3, Vol. 44, 1892, pp. 177–192.

G. R. Putnam: Relative Determinations of Gravity with Half-Second Pendulums, and Other Pendulum Investigations, *U. S. Coast and Geodetic Survey Rept. for 1894*, Appendix I, pp. 7–50; and G. K. Gilbert: A Report on a Geologic Examination of Some Coast and Geodetic Survey Gravity Stations, *ibid.*, Appendix I, pp. 51–55.

G. R. Putnam: Results of a Transcontinental Series of Gravity Measurements, *Bull. Philos. Soc. of Washington*, Vol. 13, 1895–99, pp. 31–60.

F. L. Ransome: The Great Valley of California: A Criticism on the Theory of Isostasy, *Univ. of California Publs. in Geology*, Vol. 1, 1893–96, pp. 371–428.

Bailey Willis: The Mechanics of Appalachian Structure, *Thirteenth Ann. Rept., U. S. Geol. Survey, 1891–92, Part II, Geology*, pp. 237–281.

[5] J. F. Hayford: Figure of the Earth and Isostasy from Measurements in United States, U. S. Coast and Geodetic Survey, Washington, D. C., 1909. (No number.)

Idem: Supplementary Investigation in 1909 of the Figure of the Earth and Isostasy, U. S. Coast and Geodetic Survey, Washington, D. C., 1909. (No number.)

[6] J. F. Hayford: The Geodetic Evidence of Isostasy, with a Consideration of the Depth and Completeness of the Isostatic Compensation and of the Bearing of the Evidence Upon Some of the Greater Problems of Geology, *Proc. Washington Acad. of Sciences*, Vol. 8, 1906, pp. 25–40; *idem:* The Earth, a Failing Structure, *Bull. Philos. Soc. of Washington*, Vol. 15, 1907–10, pp. 57–74.

[7] J. F. Hayford and William Bowie: The Effect of Topography and Isostatic Compensation Upon the Intensity of Gravity, *U. S. Coast and Geodetic Survey Special Publ. No. 10, Geodesy*, Washington, D. C., 1912.

William Bowie: Effect of Topography and Isostatic Compensation Upon the Intensity of Gravity, *U. S. Coast and Geodetic Survey Special Publ. No. 12, Geodesy*, Washington, D. C., 1912.

Idem: Investigations of Gravity and Isostasy, *U. S. Coast and Geodetic Survey Special Publ. No. 40, Geodesy*, Washington, D. C., 1917.

[8] See especially S. G. Burrard: Investigations of Isostasy in Himalayan and Neighbouring Regions, *Survey of India Professional Paper No. 17*, Dehra Dun, 1918. See also papers by Colonel Burrard, "A Brief Review of the Evidence Upon Which the Theory of Isostasy Has Been Based," *Geogr. Journ.*, Vol. 56, 1920, pp. 47–59; "On the Origin of Mountain Ranges," *Geogr. Journ.*, Vol. 58, 1921, pp. 199–218; and the review by A. Mosley Davies, "The Problem of the Himalaya and the Gangetic Trough," *Geogr. Journ.*, Vol. 51, 1918, pp. 175–183.

Some general conclusions from the isostatic investigations in the United States and India are:

1. The earth's crust is in a state of practically perfect isostatic equilibrium.

2. The depth to which the isostatic compensation extends is not and cannot be correctly determined, nor is it possible to determine in what manner isostatic compensation is distributed, whether uniformly with respect to depth or in some other manner.

3. If it is assumed that the isostatic compensation is uniform with respect to depth and is complete within a certain depth, then the most probable limiting depth is about 60 miles.

4. It is impracticable or impossible to determine whether the isostatic compensation is directly under a topographic feature to the extent that single mountain peaks are compensated within the column directly under them.

5. It has been determined, however, that the isostatic compensation of a topographic feature is probably not distributed horizontally to distances as great as 100 miles from the feature.

6. The isostatic compensation of topographic features is so complete that the deflections of the vertical are only approximately 10 per cent of what they would be if the land masses were excess loads on the earth's crust. Also the isostatic condition of the earth's crust is such that the gravity anomalies, that is the differences between the observed and the computed values for the intensity of gravity, are on an average not more than 15 per cent as large at stations at high elevations, as they would be on the theory that the earth's crust is rigid.

The above conclusions are in every way justified from the exact measurements that have been carried on in the United States and, to a limited extent, in other countries; though specific attention should be directed to numbered paragraph 3 above and to the assumptions preceding the concluding estimate of limiting depth of compensation. Such assumptions can of course be made the basis of further investigations that may modify the result.

There are other conclusions which seem to be justified, and some of them will be discussed below. It should not be understood that they are the only ones that can be reached; but they seem in the present state of knowledge to be logical, and they do not conflict with the existing geodetic and geophysical data.

The Rigidity of the Earth's Crust

The earth's crust must have considerable rigidity in order to maintain the irregular relief of the earth. It is true that each unit column of the earth's crust, or isostatic shell, as it has been very aptly called by Bailey Willis, has the same mass as any other unit column, but we must not think

in terms of columns of very small cross section. It seems safe to assume a unit cross section for compensated areas of 70 miles square, the approximate area of a square degree at the equator.

What the geodetic observations and investigations have done is really to measure indirectly the differences in weight of the masses in the various unit columns of the earth's crust, and these columns have been found to be remarkably near each other in the amount of their masses.

If the earth's crust were not rigid to a certain extent, mountain masses would overflow marginal areas of lower elevation; likewise, the material of a continent would overflow the ocean bottom. If there were no rigidity in the earth's crust, this process would continue until all irregularities in

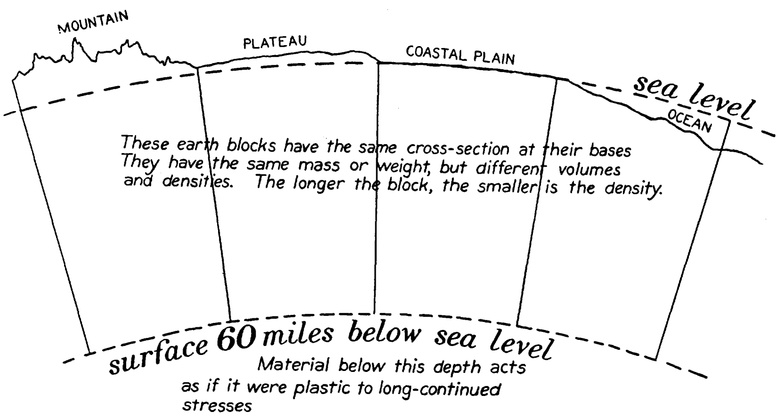

FIG. 1—Probable limiting depth of isostatic compensation.

the surface of the earth were smoothed out. There is in reality a tendency toward overflow, just as there is a tendency for any structure to collapse, but the rigidity (combined with the strength) of the material keeps it in place. Apparently the rigidity of the earth is such that this flattening out will never occur. However, the resistance of the earth's crust, while great enough in a horizontal direction to resist the flattening of the earth's surface, is not great enough to withstand the vertical stresses developed by the erosion of matter from high ground and its deposition in low areas.

Enormous loads of material are taken from mountain areas and deposited in valleys or at the mouths of rivers. If the earth's crust were of such rigidity and offered such resistance to vertical forces as to hold up the sedimentary material, this fact would be easily discovered from the geodetic data on the deflections of the vertical and the intensity of gravity. This question has been very carefully considered, and it has been found that areas of sedimentation are as nearly in a state of perfect isostatic equilibrium as more quiescent areas, geologically speaking.

As another evidence of the inability of the earth's crust to withstand a vertical stress we may cite the case of a mountain mass from which thousands

of feet of material have been eroded in recent geologic times. If the mountain were in isostatic equilibrium before the erosion began, then it certainly would not be in equilibrium at the present time if no upward movement had occurred at the base of the mountain column to offset the loss of material by erosion at the top. The mountain mass is *now* in equilibrium, and therefore as erosion progressed there must have been *in the past* a transfer of material to the column under it.

We may accept the fact that areas of sedimentation and areas of erosion are in substantial equilibrium not only in the United States but in other countries. Wherever isostatic investigations have been made the data confirm this conclusion.

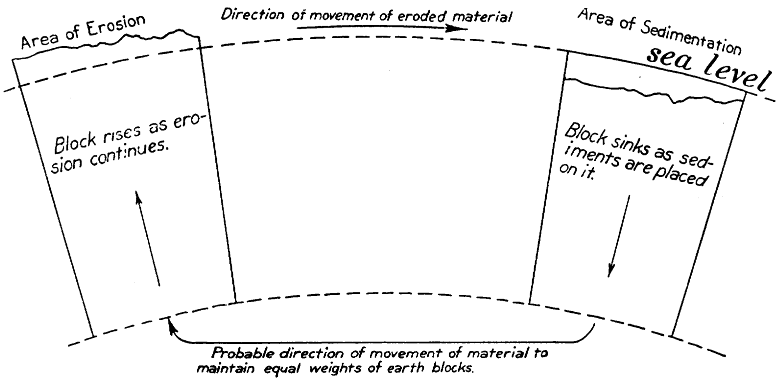

FIG. 2—The mode of compensation between a rising column in an area of erosion and a sinking column in an area of sedimentation.

ZONE OF FLOW

As the earth's crust is in isostatic equilibrium we must conclude that there is a transference of material horizontally from areas of sedimentation to areas of erosion. It is only in this way that the isostatic balance can be maintained. Assuming that horizontal movements maintain that balance, we are forced to conclude that the material at some point below the crust of the earth is of a yielding nature, much more so in fact than any matter near the surface of which we have knowledge.

Seismologic observations and those connected with the determination of earth tides, prove conclusively that the earth's material at all depths is solid. The response of the solid crust to the tide-producing forces of the sun and moon is only a fraction of what it would be if the earth were thoroughly plastic. The seismic waves that travel to a distant observer from an active earthquake center pass by a direct route through the earth, and this would not be the case if the crustal matter were liquid or if it were plastic to short-time stresses.

We have apparently to conclude that there is a zone below the isostatic shell, or the crust of the earth, within which the matter is rigid to stresses

continued over a short period, such as the tide-producing forces of the sun and the moon, but is plastic to the long-continued stresses which result from an unloading of one part of the isostatic shell and the loading of another. When we speak of long-continued stresses we have in mind stresses that last for thousands of years, that is, we are speaking in geologic time rather than in human time.

The condition of the material of the earth below the zone of flow need not be considered for our present purposes. When we speak of a zone of flow we are simply trying to visualize the condition of affairs below the earth's crust involved in the transference of material to maintain the isostatic balance, and we do not necessarily imply that this zone has limited thickness. It may be a thin zone, a thick zone, or one that extends throughout what may be called the nucleus of the earth, the nucleus being that portion of the earth below the isostatic shell.

It seems logical to assume that the flow of material, due to transference of material at the surface of the earth, must be at or below the base of the isostatic shell. In the first place the determination of the depth of the isostatic shell, or that depth within which the isostatic compensation exists, presupposes that the material above that depth is somewhat different in its behavior from the material below. If there were a transference of material within the isostatic shell, then it is rather difficult to see how there could be an isostatic compensation occurring within this moving material. If the isostatic compensation were in material that is plastic enough to move horizontally, then surely this plastic material would assume a condition of hydrostatic equilibrium within a very short time, geologically speaking. The material could not be like the outer portion of the earth, which is able to withstand the tendency of gravity to flatten out the irregularities of the surface.

The second objection to having the isostatic adjustment of flow take place above the depth of compensation is that there is an equality of pressure at the depth of compensation. At that depth columns of like cross section balance each other in pressure or weight. Now, when there is a transference of material from one column to another at the surface and the corresponding isostatic flow begins, we certainly have to go practically to the depth of compensation in order to find the hydrostatic pressure to make the material flow from the short column—the one subjected to sedimentation—to the mountain column from which the sediments have been eroded.

If we assume an isostatic flow only a few miles below the surface, should we not be trying to move material from a light block to a heavy one? In a plane of reference, say 10 miles below sea level, we might have the base of a column 11 or 12 miles in length under the area of erosion (mountains) and one of only 10 miles in length under the area of sedimentation (plains). It is evident that at a depth of 10 miles the stress difference will be from the mountain area towards the plains area. Only when erosion on the one

hand and sedimentation on the other have been so great as to cause the plains section of the crust to overbalance the weight of the mountainous crust could we expect to have flow from the plains area to the mountain area. The flow resulting would take place at whatever depth the pressure is greater under the sediments than under the mountains from which the material was eroded.[9] What is the depth at which this pressure difference is expressed in flow? Let us turn to this as the next item of enquiry. It is easy to compute at what depth the weight of a column on which the sediments have been placed will equal that of the column under the area that has been eroded if the compensation is assumed to be uniformly distributed

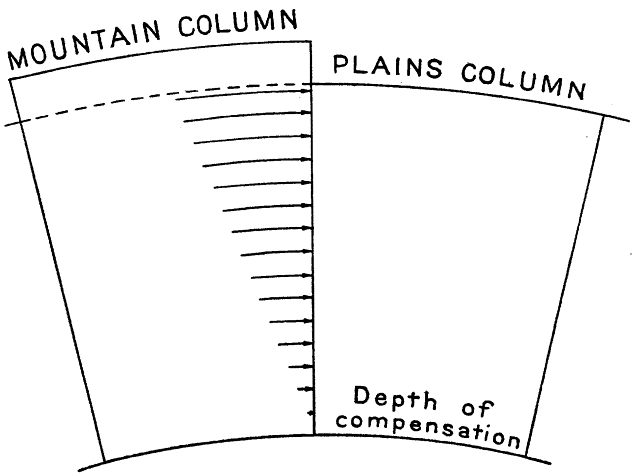

FIG. 3—Depth of compensation between mountain and plains columns when transference of material from one to the other, at the surface, is just beginning.

with regard to depth. The greater the transference of matter before isostatic adjustment has begun,[10] the nearer the surface will be the depth at which the pressures of the columns will be equal. It seems reasonable to assume that the amount of material which can be deposited before isostatic adjustment begins is quite small, less than 1,000 feet in thickness. Therefore, if we hold to the view that 1,000 feet of material over a rather extended area is the maximum that will escape isostatic compensation, then we shall find that the depth at which the flow must take place is greater than 50 miles.

This question of the depth at which the isostatic adjustment takes place is a most important one from a physiographic standpoint. If the flow occurs as a deep-seated phenomenon, we must conclude that the configuration of the earth's surface between the area of erosion and the area of sedimenta-

[9] This idea is brought out by Hayford in his article entitled, "The Relations of Isostasy to Geodesy, Geophysics and Geology," *Science*, Vol. 33 (N. S.), 1911, pp. 199–208.

[10] Undoubtedly the isostatic adjustment lags somewhat behind the transference of matter at the surface.

tion has little or no relation to the material moving horizontally at or below the lower surface of the crust. It is not probable that any wavelike distortion of an extensive character can be due to this slow movement of the plastic materials below the isostatic shell. If the flow were close to the earth's surface, say within a few miles, then undoubtedly there would be an effect on the configuration of the earth's surface by the horizontal movement, just as the flow of molten lava will greatly distort the cooler solid lava which floats on it.

It is probable that in an alluvial plain there is at least some horizontal movement of material near the surface, possibly within a mile, due to stress

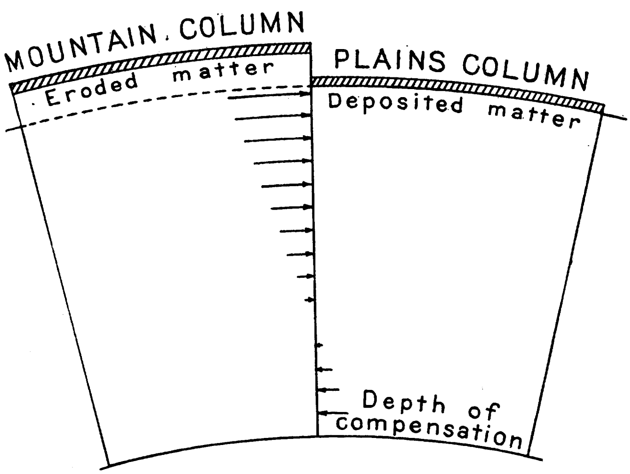

FIG. 4—Depth of compensation between mountain and plains columns after the transference of eroded material at the surface has continued without compensation by deep-seated flow. This depth is taken to exceed 50 miles for a surface accumulation of eroded material 1,000 feet thick.

differences in the unconsolidated sediments. But we should expect no movement from one block toward another of greater mass.

It is certain that there cannot be a flow of material near the surface from a narrow mountain valley back toward an adjacent mountain slope from which material is being eroded and deposited in the valley. The stress difference in the upper portion of the isostatic shell is always from the mountain toward the adjoining valley. It is very improbable that columns of small cross section are individually in isostatic equilibrium and that a small valley column could sink throughout its entire length and uplift a second small column under the adjacent mountain side. The rigidity of the material of the isostatic shell would certainly prevent such movements. The recently published views of Tandy on this subject appear to me to be in opposition to the plainest facts of physiography and geodesy.[11]

[11] E. A. Tandy: The Circulation of the Earth's Crust, *Geogr. Journ.*, Vol. 57, 1921, pp. 354–376.

Mountain Systems and Oceans Not Maintained by Rigidity of Earth's Crust

Modern investigations in isostasy lead to the definite conclusion that differences of elevation between mountain masses and continents on the one hand and plains and oceans on the other are not due to the strength of the earth's crust, but that they express the deficiency of matter under the elevated areas and the excess of mass under the depressed ones.

It should be clearly borne in mind that the continents compensate the deficiency of density under them and that the oceans compensate the excess of density below their bottoms. In other words, the land masses and the oceans are the effect of the abnormal densities rather than the cause.

If the mountain mass is not an extra load, neither is it due to regional horizontal pressure and movement. We conclude that it is due to vertical forces and movements and that an expansion of the matter under the mountain area is the most probable cause of the uplift.

The question immediately arises, what is the cause of the expansion? This is a matter that is decidedly speculative or theoretical. In two recent articles[12] I have suggested that the cause of the expansion of the material of a column under a mountain system may be due to a heating of material forming this column when it was beneath an area of sedimentation and sinking into hotter regions.

As sediments are deposited, an extra weight is added at the plane of compensation. It is probable that the sediments are so small in mass in some places that no vertical movement takes place; but we know that in other places enormous amounts of sediments have formed, as indicated by the exposed strata in mountainous regions. Nearly all mountain areas were at one time areas of heavy sedimentation, and the sediments were deposited in shallow water or not much above sea level. This process of heavy sedimentation is now going on at the mouth of the Congo, in the Indo-Gangetic region, and about the La Plata estuary.

The sediments from which mountains were formed were in some cases 30,000 feet or more in thickness. Let us assume that in some particular case this depth of sediments was six miles. As the sediments were deposited, the matter in the crust under them was forced down into regions that were hotter; and, when the base on which the sediments had been placed was depressed to the extent of six miles, every portion of the column from the base of the sediments to the depth of compensation was subjected to a temperature that was hotter by the change in temperature for a difference in depth of six miles. This change in temperature is not known; but, if the temperature gradient is anywhere near what it is for the first mile of the earth's crust, the change is very great.

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[12] William Bowie: The Relation of Isostasy to Uplift and Subsidence, *Amer. Journ. of Sci.*, Ser. 5, Vol. 2, 1921, pp. 1–20.

Idem: Some Geologic Conclusions from Geodetic Data, *Proc. Natl. Acad. of Sci.*, Vol. 7, 1921, pp. 23–28.

It is probable that a surface of equal temperature, termed "geoisotherm," will be somewhat depressed as the sediments are being placed on the surface and the column is sinking. Later the geoisotherm will rise to its normal position. In this process the material under the sedimentary area will become much hotter than it was before sedimentation began, and it is my view that physical or chemical changes or both will occur which will expand the material of the column and thus elevate the surface to form a mountain system.

This vertical movement of material would undoubtedly be accompanied by the development of inclined forces, and in some cases even horizontal ones, which would move the material in such directions as to cause the distortions that may be observed in an uplifted area. The base of a moun-

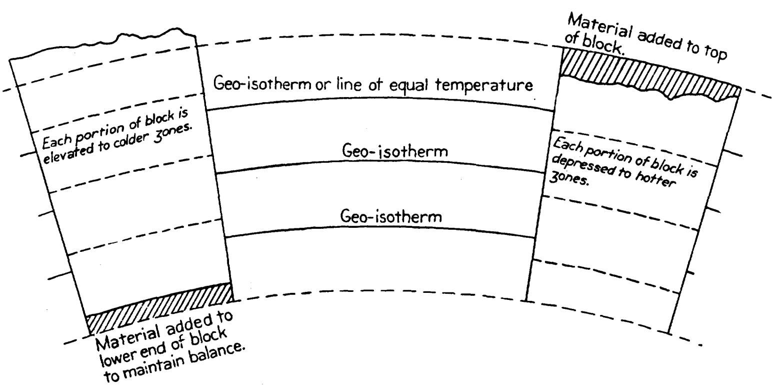

FIG. 5—Changes of temperature in rising and sinking columns to suggest the deforming effect of expansion in a sinking mass under an area of sedimentation.

tain system is usually quite large, the Appalachian system being considered as approximately 200 miles in width by 1,000 or more miles in length. This is an area quite large enough for the development of horizontal and inclined forces due to the uplift of material in response to changes in density.

It is undoubtedly true that sediments are deposited in a very irregular way. Some part of a region of sedimentation that eventually will become the location of a mountain system will naturally receive most of the sediments, but as sedimentation progresses the surface of this area may become higher, by the building-up process, than contiguous areas. When this has occurred sedimentation is then shifted to one of the lower areas, and so on throughout the history of the region. Since sedimentation takes place in different parts of the area at different times and at different rates, we should expect a large amount of distortion of the sedimentary strata during the process of subsidence under the added loads.

After sedimentation has ceased in a given region and possibly after a long period of quiescence an upward movement may occur resulting in the formation of a mountain system. During the uplift there is probably a very irregular movement due to variations in the resistance of the recently

deposited sedimentary matter and of the material of the crust below it. The different resistances would, presumably, permit the uplift to occur more rapidly in one part of the region than in another. When the uplift in one area had progressed to a point where resistance to further uplift on account of the weight of the uplifted material was greater than in an area in which uplift had been retarded, vertical movement would probably take place in the latter area.

There would be a great force acting to restrain uplift near the edges of a rising column, for it is probable that the uplift would be confined largely to the column on which sedimentary material had been placed. Probably the greatest distortion of strata would occur near the edges of the area of uplift. Thus, much of the distortion of strata which in the past has been attributed to the horizontal thrust of forces originating in the areas outside the mountain areas may be due to the different rates of subsidence and uplift in the region now occupied by a mountain system which was formerly an area of sedimentation.

Isostatic Adjustment Tends to Maintain Mountain Systems

It is possible to compute the rate of erosion over a large area, especially where careful analysis of the waters of the rivers draining the area in question has been made. This rate of erosion will vary in different parts of a continent and in different parts of the world; but it is a function of the amount of rainfall, the steepness of the slopes, the composition of the surface materials, the character of the vegetation covering, and possibly other conditions. It can be safely said that the flattening process is a very slow one and, even if there were no further uplifts due to expansions of columns of the isostatic shell, the time necessary to wear down a mountain system would be very great, and mountains on the continents would remain for a long time. But it is also very probable that the expansion of columns under areas heavily sedimented will continue in the future and form new mountain systems.

Geodetic researches indicate very clearly that mountain columns must have been maintained in isostatic equilibrium throughout the erosional period. It might be thought that when 100 feet of material has been eroded from a mountain area the mountain would be raised vertically by the same amount to maintain equilibrium. But the material that is brought into the column under the mountain area by isostatic adjustment is undoubtedly denser than the material eroded from the surface, and, therefore, not so great a volume is needed to maintain the isostatic balance. It is probable that the difference in density of the surface material and that at a depth of about 60 miles is as much as 10 per cent. When 100 feet on an average is eroded from an area, the disk of material brought into the column at its base is, on this assumption, only 90 feet in thickness, the difference in thickness of the two disks being due to the difference in density of 10 per cent.

Therefore, on the assumption that compensation at the isostatic level is taking place without delay, as an area is eroded 100 feet we should expect its average elevation to be 10 feet lower than before the erosion began. Similarly, if 1,000 feet of material is eroded, the average elevation should be reduced by 100 feet; and if 10,000 feet is eroded, the average elevation should be reduced 1,000 feet; and so on.

The process of gradually decreasing the average elevation of an area accounts for the presence of sedimentary material tens of thousands of feet in thickness which must have been eroded from mountain systems of moderate horizontal dimensions. We can see that to reduce to sea level a mountain system of an average elevation of 5,000 feet, approximately 50,000 feet must be eroded from its area.

This continued uplift of the material of a mountain during erosion probably accounts for the exposure of an igneous core. From the Rocky Mountain area there have been eroded many thousands of feet, and in places the sedimentary material has been entirely removed. This also has occurred in a number of places in the Alps, where the highest peaks are formed of abyssal igneous rocks. Without the great amount of erosion that is involved in wearing down a mountain system the originally deep-seated igneous rocks could not have been uncovered.

Does it not seem possible that, as the uplift of the mountain continues after the system has once been elevated, there should be a tremendous amount of distortion of strata due to the isostatic adjustment? I think this vertical movement accounts for much (though not all) of the rupture and distortion of the strata which in the past has been considered as the result of regional forces of different origin acting horizontally in the earth's crust.

The mountains will certainly be gradually, although very slowly, base-leveled as the results of erosion, in spite of the tendency towards approximate maintenance at the original elevation by isostatic adjustment. The differential density between the eroded material and the material brought into the base of the column in response to isostatic adjustment will eventually leave a mountain system at a low altitude. This will occur, however, only after tens of thousands of feet of material have been eroded from the area, an amount wholly disproportional to the original elevation of the mountains.

Possible Cause of Subsidence

When a mountain area has been lowered 5,000 feet and base-leveled, all parts of the original column under the mountain area have been brought possibly from 8 to 10 miles closer to the surface of the earth than they were before erosion began. After the erosion period of a particular area is ended, then it would be expected that the material in the column, which had been brought up into colder regions, would lose some of its heat and that chemical or physical changes might occur that would tend to contract it. It is prob-

able that the geoisotherms, or surfaces of equal temperature, were bent upwards in the upward movement incident to the isostatic adjustment of the column and that these geoisotherms are gradually depressed to their normal depths after the active erosion of the surface of the column has ceased. As this cooling process goes on in the column under the former mountain area it is possible that the surface of the earth may be depressed to sea level or even below it. When this has occurred, then the area may again become one of sedimentation; and the process of depositing the sediments that may eventually be thrown up as a mountain system is started over again. It may be that mountain areas have been what may be called active regions for geological ages past and that there has been a succession of sedimentation, mountain uplift, base-leveling, repeated sedimentation, a second uplift, and so on. It is possible also that there are areas in which heavy sedimentation has never occurred and which have never been elevated into a mountain system or a high plateau.

Outstanding Problems

A number of problems will have to be solved before we know very much about the causes of the uplift of continents above the ocean level and the processes that are involved in the uplift of an area that was once at low altitude. For example we should like to know what caused the first irregularities in the surface of the earth. There must have been some areas higher than others in order that there could be initial erosion and transportation of material.

It is possible that there was an initial difference in the density of the material in different parts of the earth's crust causing large differences in elevation. It may be that the average elevation of the areas comprising the present continents has always been greater than the average elevation of the areas now occupied by oceans. This does not mean, however, that there have not been decided changes in the elevation of parts of the continents. At times parts of the continents have been under water and at other times many thousands of feet above sea level, forming mountain masses. Changes are continually taking place in the density of the materials in the isostatic shell which cause considerable changes in the elevations of affected areas. Large changes may have occurred in the elevation of the bottom of the oceans. In places mountains may have been formed reaching to the surface, and at other places there may have been a sinking of the bottom. Such changes must be the result of changes in density and must be due to changes in volume rather than in chemical composition. Dr. Henry S. Washington has been working on the matter of the relation of the general elevation of an area to the chemical density of its igneous rocks. He has found that the average density of these rocks occurring on continents is less than that of igneous rocks occurring on oceanic islands. It appears from his work that the chemical density of the material in the crust under the oceans is greater than that under the continents.

To point to another problem, it is of the greatest importance that an apparatus be perfected which will permit the accurate determination of gravity at sea. Much work could be done with such an apparatus at small expense, and the results would show very definitely whether the earth's crust under ocean areas is in the same state of equilibrium as under the land. In my opinion such observations will prove that isostatic adjustment is world-wide. The geodetic institutions of the countries of the world should carry on isostatic researches, using the accumulated data in the form of deflections of the vertical and the intensity of gravity which they now have at their disposal. Gravity observations should be made in many land areas of the earth which have not yet been explored so far as gravimetric surveys are concerned.

Much remains to be done, but the isostatic investigations of the past twenty years have shown that the earth's crust is in a state of equilibrium. This work has been done by the geodesist, and we must now look largely to the geologist to apply the knowledge gained by the isostatic investigations to the interpretation of the forces and movements which have brought about and maintained the isostatic equilibrium.